ENGINEERING CASE LIBRARY

ECL 161

DEVELOPMENT OF A STAINLESS STEEL TRASHRACK

 Written by Ronald Jay Shuman with support from the National Science Foundation. The cooperation of the Market Development Department of The International Nickel Company, Inc., is gratefully acknowledged.

DEVELOPMENT OF A STAINLESS STEEL TRASHRACK

INTRODUCTORY

The Gateway arch, towering 650 feet above the St. Louis Riverfront, has been admired by millions of Americans. The arch is faced with 900 tons of stainless steel, making it the largest structure of this material in the United States. The *second* largest stainless steel structure in the U.S. is of a much more prosaic nature—few Americans, other than corrosion engineers, have admired it; even fewer have seen it. Nevertheless, this structure, the trashrack system for the intake of the Oroville Dam powerplant, is interesting both as a technical achievement and as an example of the way engineering innovations are accomplished.

I. BACKGROUND

Eighty percent of the people in California live in metropolitan areas from Sacramento to the Mexican border. Seventy percent of the state's water supply originates north of the latitude of San Francisco Bay. Throughout the state, the bulk of rainfall occurs in a few winter months, while the summers, when water needs are greatest, are long and dry.

State Water Project. For these reasons it has been necessary to redistribute the state's water supply, usually by conserving stream runoff in surface storage reservoirs and transporting the regulated supplies to areas of use. In 1961 the people of California approved a 1.75 billion dollar bond issue to finance the State Water Project, an interlocking network of dams, reservoirs, powerplants, and aqueducts which ultimately will provide 4.23 million acre-feet* of water annually to water-deficient areas in central and southern California. (Exhibit 1)

The Oroville Dam. The Oroville Dam and Reservoir, located near the community of Oroville in North-Central California, constitutes the key water conservation facility of the project, providing flood control and a source of hydroelectric power as well. The dam itself is 770 feet high (this is roughly equivalent to the height of a 62-story building and 40 feet higher than Hoover Dam) and nearly twice as long as the Golden Gate Bridge; it is the highest earth fill dam in the world and the highest of any kind in the United States. The dam embankment, built over a concrete core block, contains more than 80 million cubic yards of fill material; the reservoir it impounds (Lake Oroville) contains 3.5 million acre-feet of water which is gathered during the winter months, when the rivers are full, then released downstream when water is scarcest in the southern regions. (Exhibit 2)

Powerplant Intake Structure. The Hyatt Powerplant is located under the left abutment of the dam in an immense cavern 550 feet long, 69 feet wide, and 120 feet high. Water to spin its six generators is drawn from the reservoir through a shuttered intake structure which, in addition to performing the usual functions of an intake for a hydroelectric project, allows temperature control of the water passing through the powerplant. This intake permits selective entry into the powerplant of water of any temperature from the warmest (65 to 67 degrees F) to the coldest (42 to 46 degrees F) available in the reservoir. To provide further control of discharge temperature, the two powerplant penstocks are serviced by separate intake channels, each of which can draw selectively from

*An acre-foot of water will cover an acre of land to a depth of one foot and is equivalent to 325,900 gallons.

any level in the reservoir between Elevation 900 and Elevation 615. Thus, when temperature requirements dictate, sun-warmed water from the uppermost 40 to 50 feet of the reservoir can be skimmed off by the intake system, and the result is a temperature gain of as much as 25 degrees F in the stream release.

Had this rather elaborate temperature control system--which turned out to be an important factor in the choice of stainless steel for the trashracks--not been included in the intake design, downstream users of water from the reservoir would have suffered. For example, at certain times of the year such fish as trout, salmon and steelhead require very cold water, while at other times relatively warm water is needed for rice irrigation.

Intake Structure Detail. The intake consists of two parallel, rectangular channels, approximately 650 feet in length, open at the top, and situated on a 1.9 : 1.0 slope along the side of the ridge comprising the left abutment of the dam as shown by the schematic cross section in Exhibit 3. At the top end of the channels is the Operating Deck Structure which includes five bays for storing and maintaining the shutters and a large gantry crane for handling them. (Exhibit 4) The position of the openings formed by these shutters determines whether warm water from the top of the reservoir or cold water from a lower level will be drawn off.

Trashracks. Floating trash, logs, and submerged debris that would interfere with the operation of turbine mechanisms are prevented from entering the intake channels by a system of coarse screens, or grids, called trashracks. (Exhibits 5, 6) Of the 650 foot total channel length, 600 feet are open to the lake and must be protected by trashracks. Roughly then, a surface area of 70,000 square feet must be covered by trashracks for the intake system to function properly.

Ordinarily trashracks are made of mild steel. This material is easy to fabricate and relatively inexpensive; a great deal is known about its properties and its use in structural elements. So, mild steel, or "low carbon steel" as it is sometimes called, would have been the obvious choice for the Oroville intake racks. To see how stainless steel came to be chosen instead--over mild steel and a number of other alternates--we need to look more closely at the history of the design.

II. INTERNATIONAL NICKEL INVOLVEMENT

Origins of the idea for the intake rack design

By the early sixties, when the preliminary designs for the Oroville Intake Structure were begun, The International Nickel Company, Inc. (Inco) had already investigated the idea of using stainless steel as a material for trashracks. In 1961 Inco market researchers reported that some small painted mild steel racks were causing trouble. These racks, which were stacked vertically in guides to cover a large intake, tended to rust together making it nearly impossible to remove them for cleaning. This trouble was cured by using stainless steel pins and guides at the points of contact between racks.

To the INCO Market Development engineers, the corrosion resistance of stainless steel in fresh water and its mechanical properties suggested an attractive solution to the problem of trashrack maintenance--rather than merely substituting one material for another, why not attempt a new design which would take advantage of

stainless steel's high strength? They hired a consultant named W. R. Petri. Using the mild steel design and requirements as a guide, he designed a lightweight, mechanically equivalent structure in stainless and demonstrated that at roughly one third the weight of the mild steel structure, it would be economically competitive. The basic concept for Petri's stainless steel design is the use of hollow bars instead of solid bars. This light-gage design places the metal at and near the surface where it is most effective, rather than distributing it over the entire cross-section. (Such a design would not be practical in mild steel, because the combination of thin walls and large surface would be too vulnerable to rust.)

Inco establsihed a Market Development project and circulated to its district offices a memorandum describing in some detail the results of Petri's investigation.

Mr. C. M. Schillmoller, who was an Inco District Office Representative in Los Angeles, was responsible for seeking opportunities to introduce this new concept on the West Coast. He presented the material to the California State Department of Water Resources where designs for two trashracks, one at Thermolito (see map, Exhibit 2), and one at Oroville (not the sloping intake rack, but a much smaller one) were under consideration. And, as he describes it, he "challenged these people, as they were deciding the Thermolito and the Oroville Dam Diversion Tunnel trashracks, to consider stainless steel as the *alternate choice*, to make designs both ways, carbon steel and stainless, to see if they could realize equivalent cost on the basis that stainless would weigh one-third of the weight of carbon steel."*

*This, along with Mr. Schillmoller's subsequent comments, was recorded by the author during a telephone interview in April, 1969.

The California engineers proceeded, with Mr. Petri's help, to design the racks in stainless. Stress analysis studies of the design convinced them that the weight saving and corrosion resistance of stainless racks could be used to advantage. Also, because these units were to be used during the pumping cycles to the storage dams and lifted during the generating cycle, enough money could be saved on hoisting equipment alone to pay for the difference between stainless steel and carbon steel trashracks. Consequently, stainless steel racks were fabricated and installed at both locations. These were the first transformations of Petri's stainless steel concept into functional designs and they easily eliminated carbon steel from consideration. But, as we are about to see, such transformations are not always without problems.

"At that point," Mr. Schillmoller says, "the next step I took was to consider what aluminum could do as a competitor because the moment we could show a weight saving of one-third, aluminum could perhaps save even more. But we found that aluminum could not do the same because of welding problems and weakness in the welded areas. Our design was based on a ¼-hard (quarter-hard) stainless steel that would only reduce the strength in the weld by 15%, whereas with aluminum the strength in the weld would be reduced by 50%. So, aluminum did not come through in the comparative design and was further eliminated from competition. At that point we were only talking about a stainless rack of 30,000 pounds, a small one, and not many people got very excited about it."

The earliest designs for the Oroville Dam Intake Structure did not include provision for drawing water from various levels of the lake. So when, in 1962, engineers at the California Department of Water Resources began working on a preliminary design for a trashrack system, they were dealing with

a comparatively small surface area to be protected. As we have already seen, mild steel would have been the obvious material to use; but the engineers responsible for this design recognized that mild steel would be less than an ideal choice. They knew, for example, that the use of mild steel would require the traditional method of controlling corrosion, namely: (1) the use of a "corrosion allowance," an increase in metal thickness over that required for structural integrity, (2) a protective coating (coal tar epoxy) and its periodic replacement (a nearly impossible task considering the depth of submersion of most of the system), and (3) a cathodic protection system. The Department engineers wished to avoid all the problems associated with corrosion and the conventional methods used to minimize its effects upon mild steel.

Perhaps these anticipated difficulties help to explain why, when Mr. Schillmoller appeared with his documentation in support of the stainless steel idea, he was received with some enthusiasm. In fact, Mr. Art Bunas, who was in charge of the design, and his staff had already considered a number of other materials; all, for one reason or another, had been rejected. When they conducted some preliminary studies of stainless steel, the California engineers found that the family of austenitic stainless steels (the 300 series) had many desirable properties, notably strength and resistance to corrosion not only on the surface but throughout the entire section.

The Department engineers were not yet moved to abandon the mild steel design altogether. They decided instead to proceed with more detailed designs in both materials. To make the comparison meaningful a considerable amount of basic design data for stainless steel had to be developed; representatives of stainless steel producers and fabricators and Inco staff personnel assisted the Department of Water Resources in the gathering of these data.* Then they were able to proceed with parallel design studies.

Mr. Schillmoller was anxious to see the mild steel alternate eliminated before bids were accepted on the project. This was important, he recalls, "because earlier I had taken the rack concept out to Bechtel Corp., who were working on a design for East Bay M.U.D. (Municipal Utility District) for trashracks and I challenged them to take the alternate route. They got no quotations in stainless steel, however, because the supplier group was accustomed only to dealing in carbon steel and could make a bid in a matter of ten, fifteen minutes in carbon steel, and I don't think they were as capable to make a good bid in stainless steel so they were reluctant to bid it." So, it became obvious that carbon steel had to be eliminated as the alternate for the Oroville Dam trashracks to avoid a similar occurrence.

The question of cost was, of course, taken up in the parallel design study. Department engineers estimated that a unit price of $1.90 per pound of stainless steel, delivered to Oroville, would be a first cost break-even price when compared to the coated, protected, mild steel system. Independent quotations from three stainless steel fabricators, who had been briefed by Mr. Schillmoller on the stainless trashrack design, indicated that this price could reasonably be expected.

In 1963 the temperature selection refinement was added to the intake system and a major redesign of the intake structure was started. Now, with a much larger surface

*References 1 to 14.

area to be protected, the advantages of the lighter weight stainless steel rack design became even more apparent. "The change to use of shutters to control water temperature," Mr. Schillmoller recalls, "was what really made the stainless steel go. At that time a young engineer by the name of Paul Gilbert was assigned to the project and the design was begun in earnest."

Having already rejected the martensitic family of stainless steels (the 400 series) because of inadequate corrosion resistance in this application, the Water Resources Department engineers now had to decide which of the austenitic types to use. They considered three types: 301, 304, and 316. Type 301 could be given the best mechanical properties but had questionable post-welding corrosion resistance. Type 316 had the best corrosion properties under any conditions but was too costly. This left type 304 (18 CR-10 Ni), which seemed to represent a good compromise between all the design criteria they applied: it was resistant to corrosion in most natural environments; could be machined reasonably well; could be formed--although it work hardens and must be reannealed if worked too much; could be cold-work hardened or tempered; was weldable so long as proper controls were applied; and was available through warehouses and suppliers in most thicknesses and widths as well as many shapes including standard shapes and tubes. Finally, the cost of type 304 was equal to or lower than that of any stainless in its class. So, with a few exceptions, type 304 was selected to be used for the trashrack system.

III. THE STAINLESS STEEL DESIGN

By late 1963 the first detail design of the intake system, including shutters and trashracks, was nearly complete.* Problems were expected—they arose. But the development of hardware seemed to go smoothly enough. (Here, as we shall see, there was still to be a surprise.) Meanwhile, there was another variety of problem, the "human factors," that had to be dealt with—soon, before bids were solicited.

Fabricators tend to behave conservatively; they are wary of that which is new, unfamiliar; a stainless structure of this size was extraordinary. Schillmoller was sure that the fabricators would react cautiously. But the size and uniqueness of the job had attracted the attention of a number of suppliers. U.S. Steel, Allegheny Ludlum, Republic, and other companies had begun sending representatives to Sacramento to learn about the application. "During that period," Mr. Schillmoller says, "we came across many stainless steel design problems. I believe that staying with them during this critical period of three or four months, helping them out every time a problem arose, secured the position of stainless enormously. Because the people there, as I say, got emotionally involved once it got started and as we stayed with them and solved the problems, they got themselves committed."

Suddenly in 1964 it appeared that the mild steel alternate had not been eliminated after all. In the design as it then stood, the *framed* stainless trashrack panels were to be supported between large concrete arches and concrete crossbars, but the project engineers discovered that the intake foundations could not carry the extra

*The stainless steel components of the shutters required only conventional design and, therefore, are not discussed in this case.

weight of this concrete "egg-crate" structure. Replacing the concrete arches with carbon steel arches appeared to be a distinct possibility. Then the question arose: Why use stainless steel trashracks if they must be supported on a carbon steel structure?

Schillmoller arranged to have Inco's consultant, W. R. Petri, brought to Sacramento. Working with Paul Gilbert, he developed an all-stainless design which would give the desired strength to support the trashracks. Unfortunately, as Mr. Schillmoller recalls, "determination of the weight indicated that the overall product would be about 35% more expensive going this route than with all mild steel." Therefore, a big change in design had to be made. It was decided to eliminate all the *frames* from the trashrack panels and have the stainless trashbars themselves transmit the forces from one arch to the next, thus becoming an integral part of the total structure. Once this concept was perfected, calculations showed that enough weight was dropped to return to equal cost with carbon steel, with the added advantage of a better looking installation. Disaster averted, detail work on the final design could proceed. Mr. Schillmoller concentrated on preparations for bidding, now close at hand. At this time, about fifty stainless steel fabricators visited Sacramento. The idea was to expose them before the bidding, to the design features involved and "to show them how they could best make the equipment and how they could do it in the cheapest way, by setting up a sort of a layout on the ground, fitting in the pieces, and welding them in this arrangement so that all arches and all racks were exactly the same shape as they came through it."

Finally, an interesting stipulation was included in the specifications. "Normally," Schillmoller says, "the state has to give the contract to the lowest bidder, never mind their qualifications. To get the quality they wanted, which meant more expenses in supervision, the State took the rather unusual step of including a provision that bidders had to have proof of capability in fabricating stainless steel during the past three years and have a metallurgist on the team. On this basis, the Department was able to assure themselves that only people really qualified would bid on this project."

The bidding took place in 1965. Paul Gilbert, in a paper presented before the National Association of Corrosion Engineers in November of that year, made the following observations:*

> *The selection of stainless steel as the structural material for the trashrack system was made on the basis of an economic comparison of expected costs. The estimated break-even price with a coated carbon steel system, considering first cost alone was reduced in the later design studies to $1.73 per pound of stainless, delivered to the site. At that price, the stainless system would have been the least expensive alternate regardless of future maintenance considerations. The bid price received for the stainless steel work proved to be even more favorable than was expected. The overall average for the whole 730,000 pounds of stainless was $1.16 per pound. There were 14 bidders for the job. The range of bids was from $2,022,340 as a high to $846,336 as the low. There were four bids under one million dollars. The*

*"Trashrack System Design for the Oroville Dam Powerplant Intake." Details of the design, which follow, are also taken from this paper.

second low was within one quarter of one percent of the low. The engineers' estimate was $1,264,674.

Overall economy is illustrated here. The cost of raw materials is only part of the total cost of any fabricated assemblage. In the case of stainless steel, material costs can represent anywhere from 15 percent up to 80 percent of the total cost depending on the alloy used and the configuration and fabrication requirements. Probably the one most important item to keep in mind when designing in stainless steel, and being aware of cost, is that the total cost of the finished, in-place framework must be the concern. Overall economy will include optimum material selection, fabrication techniques, tolerances, availability of capable fabricators, transportation, handling and installation requirements, and acceptance testing.

Design Details. In the final design there were 180 similar, segmented circular support arches, braced to resist loads applied out of their plane. Affixed to these arches, covering the openings between them, were 824 panels, each a simple rectangular framework of trashbars and connecting members (see Exhibit 7). The arches were shop assembled by welding and field assembled by bolting at specified joints; the panels were installed by bolting directly to arch flanges. Since each of these components–support arches and panels–was to be duplicated so many times, a few unrequired ounces of material per unit length, or a difficult to assemble detail, would be extremely costly; therefore, design criteria had to be carefully determined.

Paul Gilbert and the Department engineers evaluated various loading conditions (structure dead loads, hydrostatic live loads, hydrodynamic seismic loads, wind and wave loads, support deflection and rotation stresses, thermal change stresses), then used computer techniques to produce both stress and deflection analyses. More details on loads are given in Appendix I. Out of these efforts came a rather elegant design that was exceedingly "clean" in appearance. Consider, for example, the shape of the support arches–it had to be structurally efficient, economically fabricated, and easily framed to other members through simply derived connections.

A typical arch (see Exhibit 8) is laid out as a circular arc and then segmented with straight line tangent pieces; it is rigidly fixed to its supports through bolted base plates. Using a series of straight line tangent elements greatly simplifies fabrication and field assembly because each arch can be built up from repetitive pre-assembled subunits. The straight line segments also make connection details between panels and arches very simple.

To establish the length of each segment the designers optimized several variables–the number of sections to be used in each arch; the resulting number of flat trashrack panels required; the size and weight of these panels for ease of handling; and the departure of the arch centerline from the true circular arch. They found that a configuration with nine segments approximately six feet long satisfied all of these conditions (Exhibit 8).

A typical arch cross section (as shown in Exhibit 9) reveals that the arch is a "hybrid" section made up of a rectangular box shaped web-core of annealed material

and flat, high strength flanges, both fabricated from type 304 stainless steel. More details on the arch design are given in Appendix II.

Two main factors, the tonnage of material required and the difficulty of fabricating the material into a structure, affect the economics of design in stainless steel. By using light-gage metal design techniques and the "hybrid" beam idea, the designers were able to achieve an optimum combination of strength with material utilization and ease of fabrication.

Exhibit 10 shows a typical trashrack panel, composed of 14 trashbars and 4 support members; it weighs approximately 350 pounds. Of the 824 panels, over 600 are identical, and the rest are only slightly modified (for example, the panels used to cover the ends of the support system are trapezoidal rather than rectangular). This uniformity reflects what Mr. Schillmoller described as an early refinement of the design, "a standardization of all shapes and forms of the arches and of the oval shaped trashbars themselves, standardizing the shapes right through the whole project which eased up at the fabrication stage tremendously."

A close look at some representative details reveals that, for all their simplicity, these panels were meticulously designed: the trashbar (Exhibit 11) is actually a specially designed hollow tube section made of ¼-hard 304 stainless; more than 154,000 feet of this tube were required to build the trashracks. The seam welds used to produce the tube from ¼-hard strip are of particular interest--they were specified to be located within plus or minus 5/8-inch of the midpoint of the 3-1/16-inch side. "In all the components that had high stresses," Mr. Schillmoller says, "we put the welds in a location where the stress was not high. Take, for example, the oval shaped tube. The easiest way to make it would be to put the welds at the top. But we put them on the side. The way the bar was sitting in the extrusion, it was only welded at the two sides, not at the nose or top where the high stresses are. It's welded where the stresses are lowest. A lot of thought went into this so that no welding was taking place at the high stress locations."

To prevent corrosion at the junctures of trashbars and their support angles, a special connection was designed (Exhibit 12). The point of highest stress for the trashbars is over the support angles. By punching the bottom of each trashbar slot in the angles to a one-inch diameter circle, a 1/8-inch clear space is provided all around the ¾-inch diameter semi-circle of the trashbars--the most highly stressed portion of the trashbar cross-section. This overpunching also provides a natural limit or boundary for welding the trashbar-to-support angle connection. Finally, the support angles serve as a fabrication jig that becomes part of the completed assembly: when fixed to a flat surface, four support angles, slotted to receive the trashbars, are all the jig required to assemble all 824 panels.

CONCLUSION

Once the bidding was over and a contract had been let, Mr. Schillmoller's job, at least the technical part of it, was done. There were, however, still some marketing details to be arranged. He encouraged Paul Gilbert to write a technical memorandum stressing the design features incorporated in the Oroville project, and this paper was widely circulated within the department and to such groups as the Bureau of Reclamation and the Army Engineers. As a result the intake trashracks for the Castaic Dam in California have been designed in stainless

steel and the U.S. Army Omaha District is considering stainless for the Kaysinger Bluff Dam. In Canada, stainless designs have been made for the trashracks at the Peace River and Churchill Falls Dams.

As this is written three men coast toward the moon. Concluding our telephone interview–Palo Alto to New York, dialed direct, Mr. Schillmoller told a story with a fascinating theme: the technology that has brought us to a new frontier gives us small innovations along with the grand. "Another thing you would like to know is this, that when Paul Gilbert was practically all through with the project, he reanalyzed the situation with their own computers and many of the pieces which initially were designed in ¼-hard, and in the arch structure ½-hard, as a result of this computer study were downgraded to annealed stainless and to ¼-hard stainless, because the computer study that he made showed clearly that they didn't need the extra strength. Then, when management didn't believe this, they sent the same information to Aerojet engineers in Sacramento; they made an independent confirmation of the design parameters, and confirmed the results. So the thing was technically proved independently by the Water Resources people and by Aerojet General in Sacramento. And this gave us quite a bit of confidence too, that we seemed to be slightly overdesigned."

EXHIBITS, ECL 161

---

*Note: Photographs except Exhibit 6, by the author. Drawing for Exhibit 3 is from Reference 19, other drawings from Reference 15.

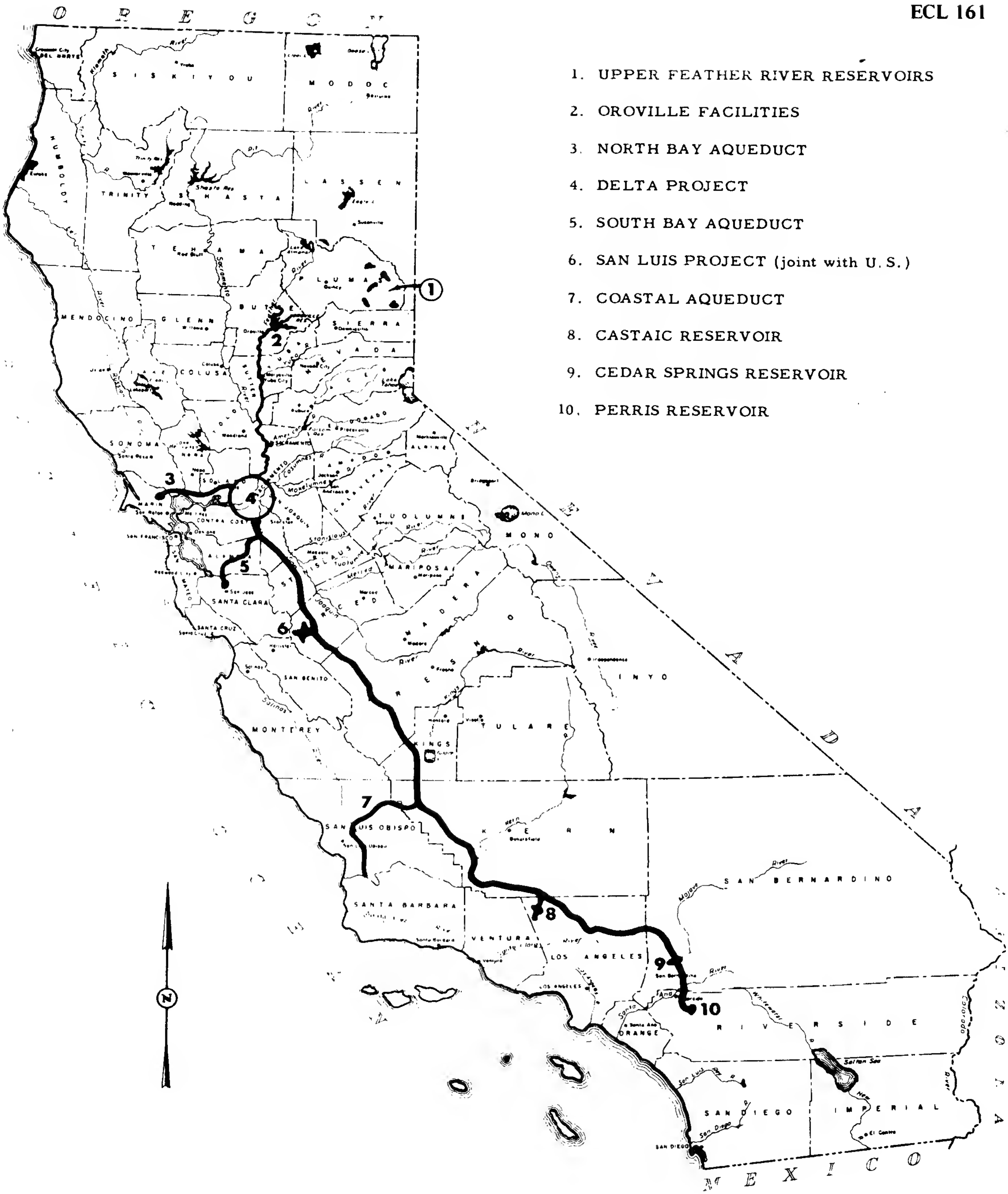


Exhibit 1 (Map) California State Water Project

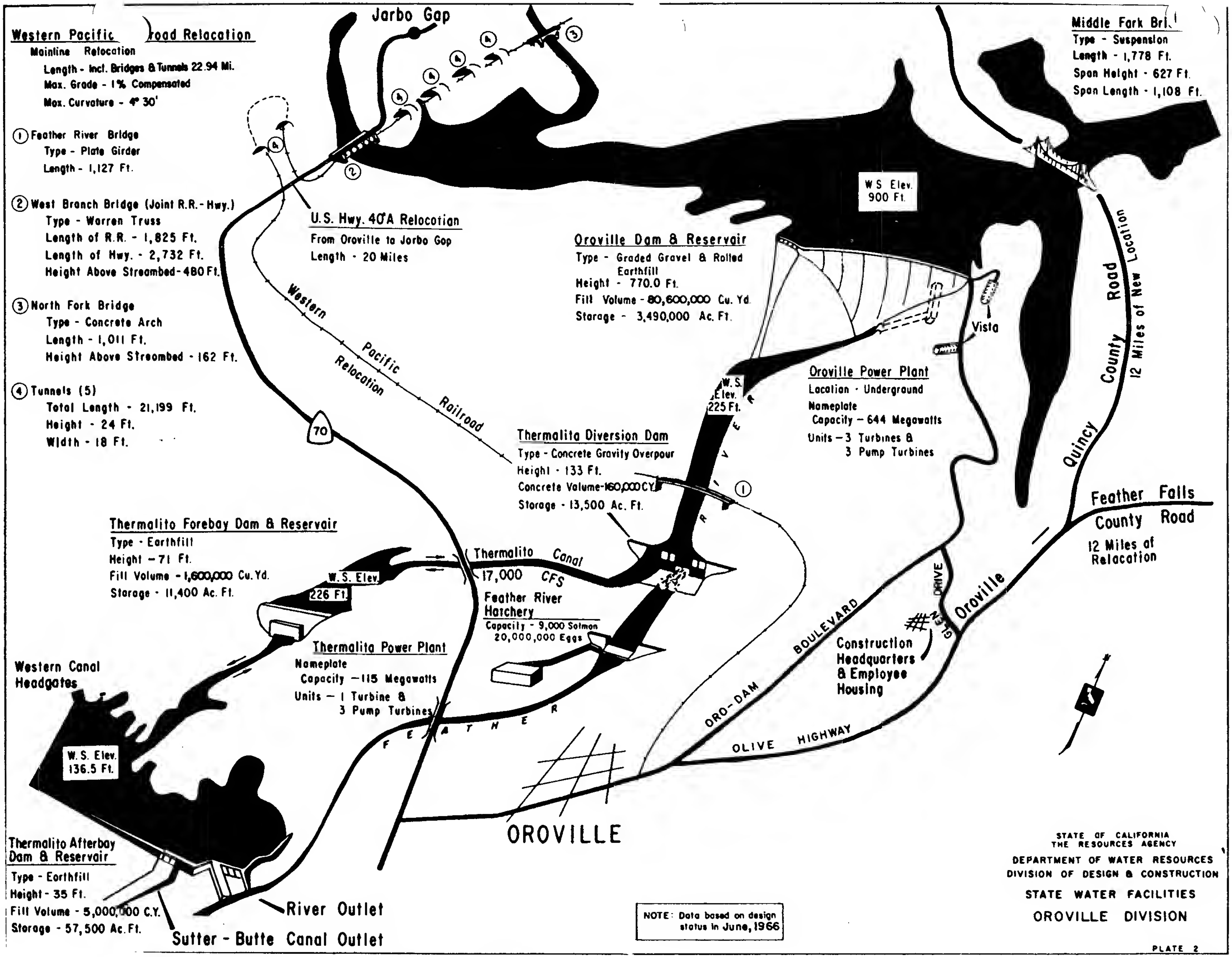


Exhibit 2 (Map) Oroville and Thermolito Installations

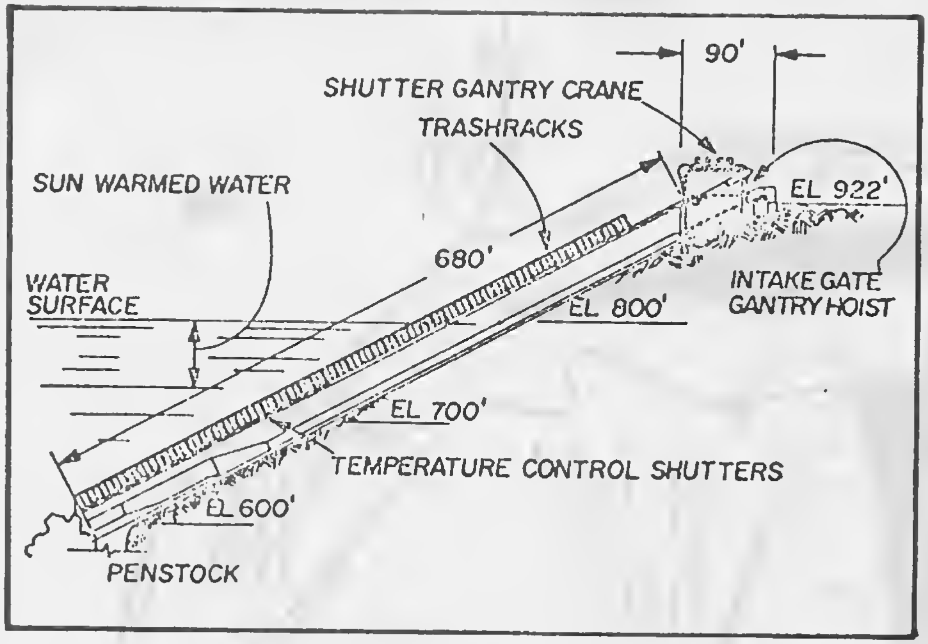


Exhibit 3 (Drawing) Schematic Cross Section of Intake System

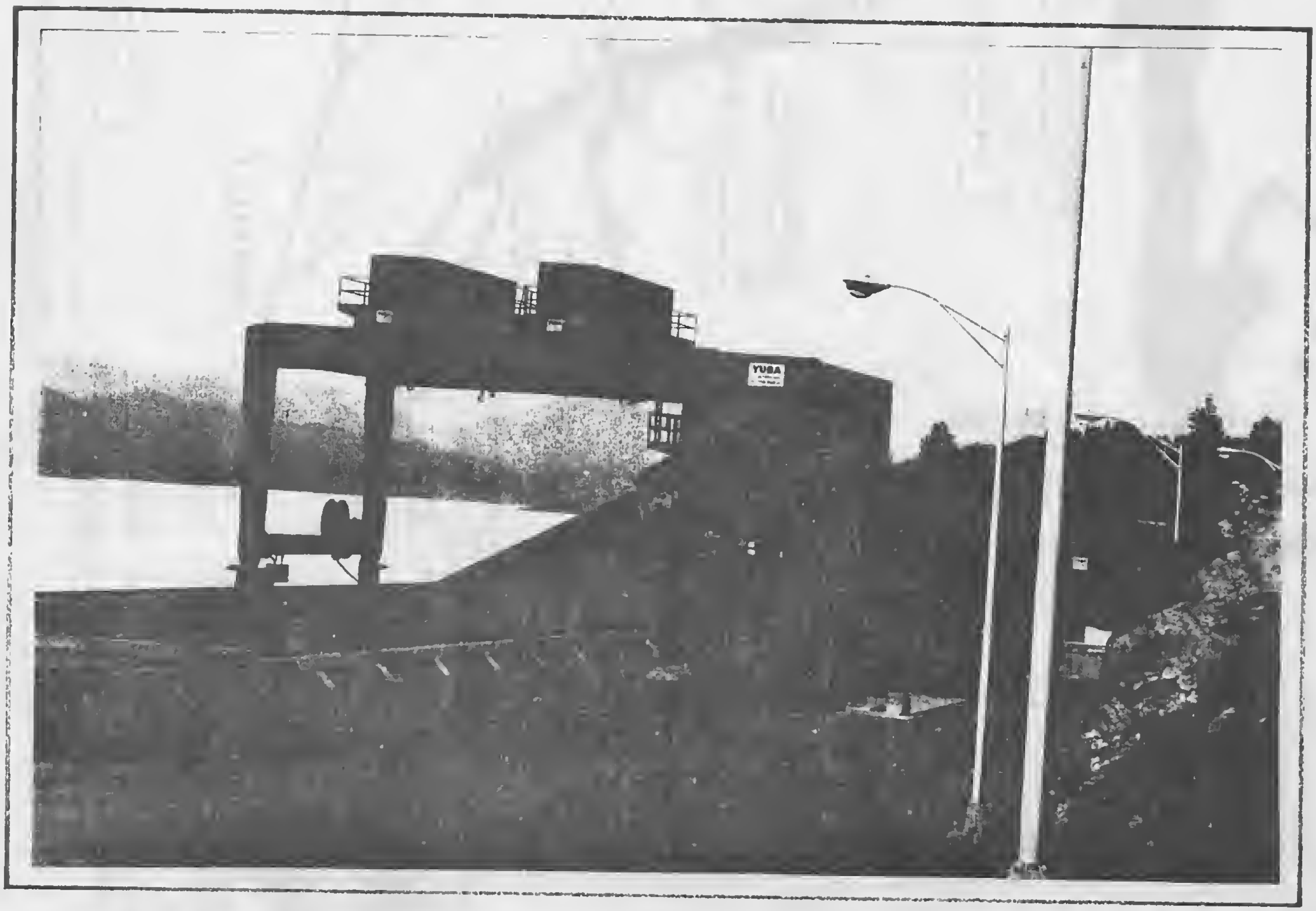


Exhibit 4 (Photograph) Operating Deck Structure Showing Storage Bays and Gantry Crane

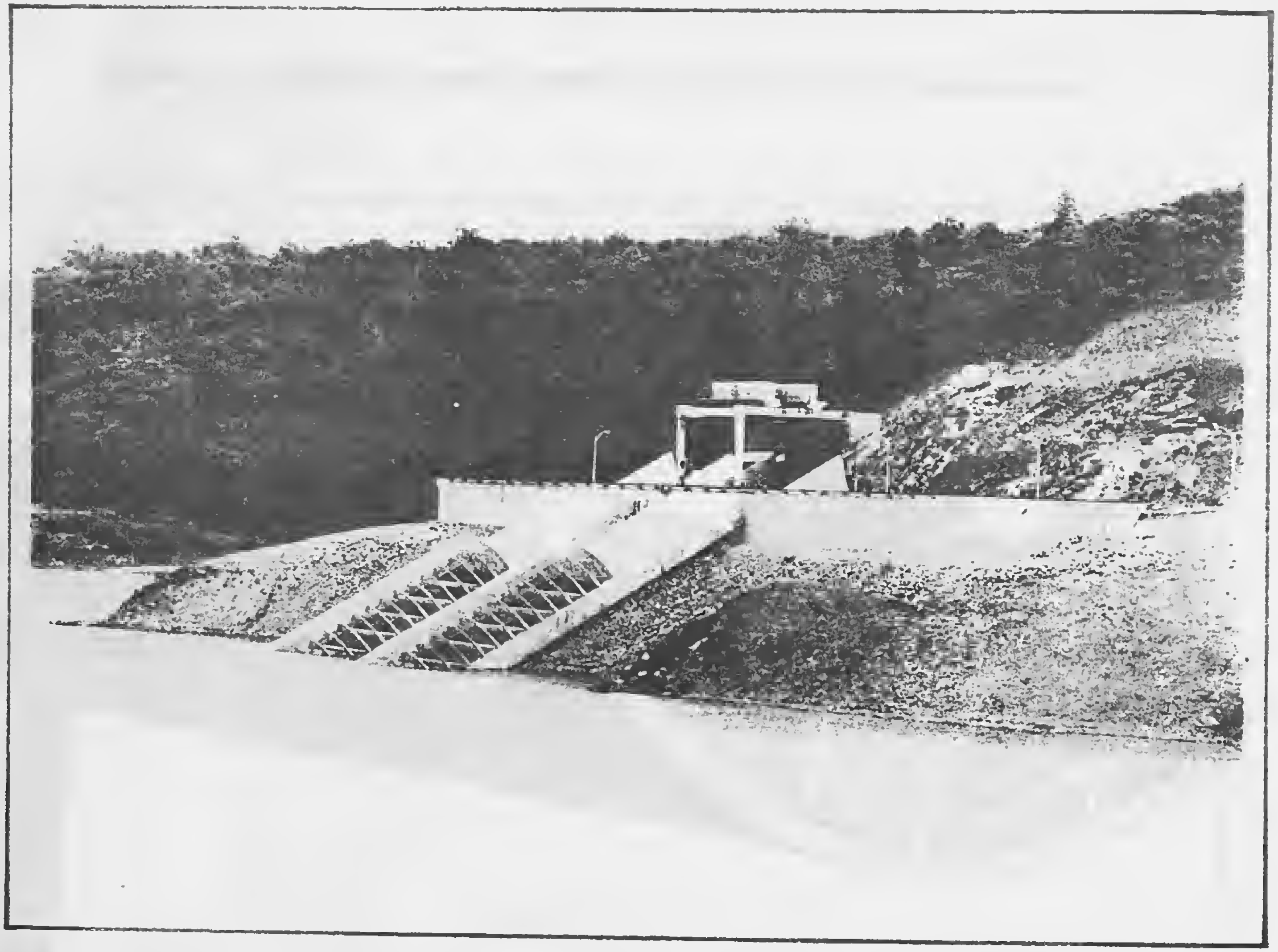


Exhibit 5 (Photograph) Operating Deck Structure and Trashracks from Dam Embankment

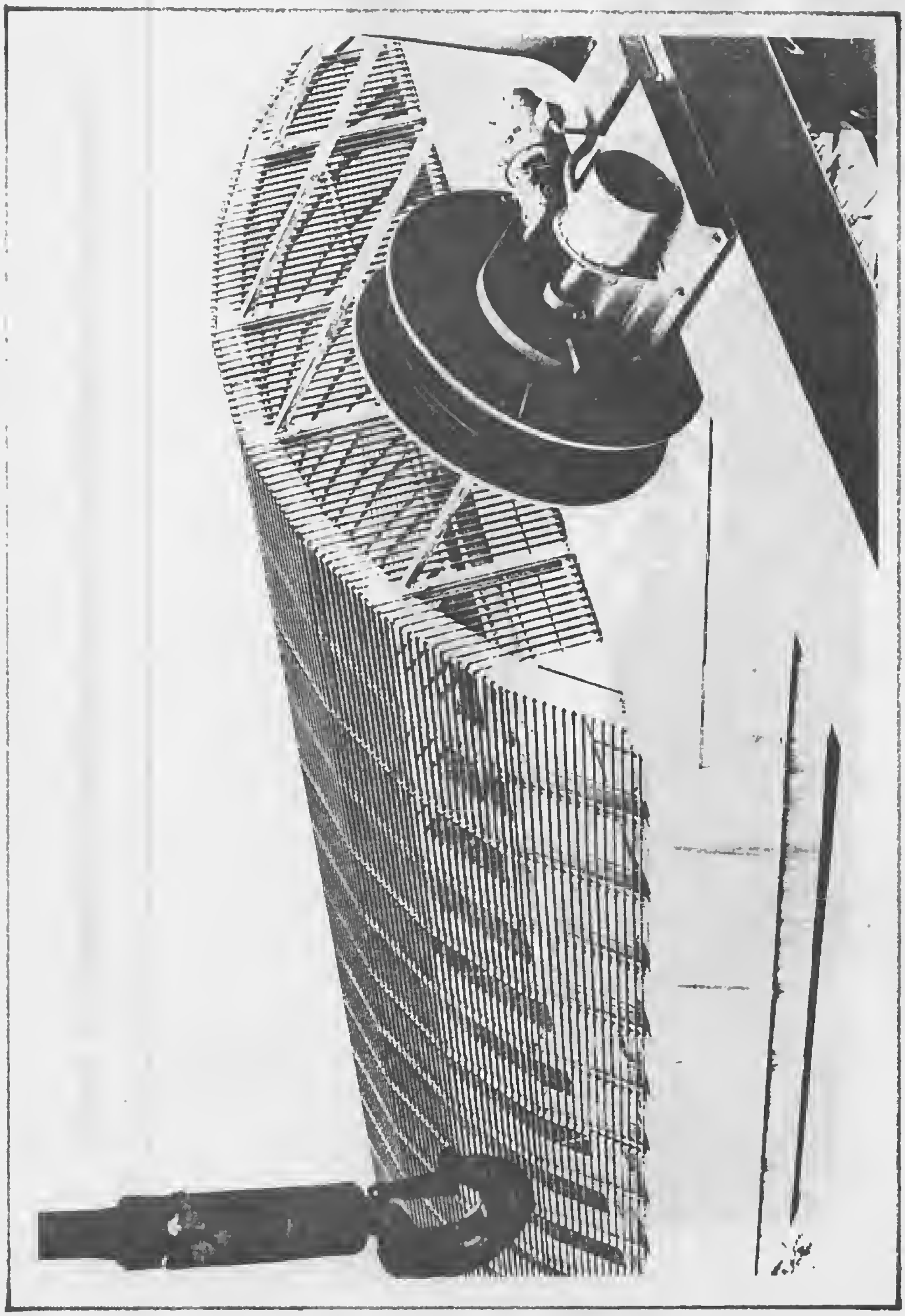


Exhibit 6 (Photograph) Trashrack Installation Detail Showing Top of Intake Channel

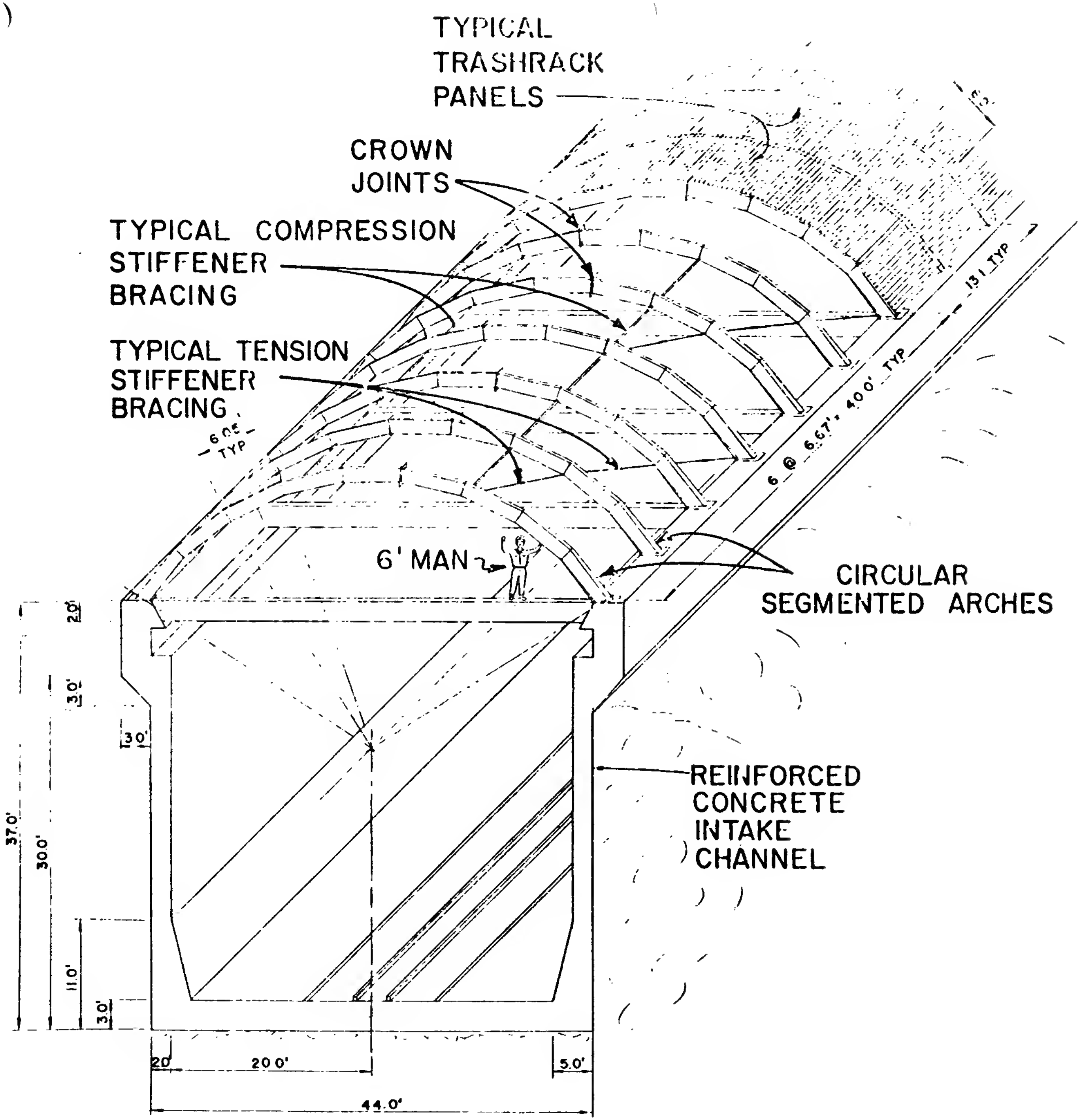


Exhibit 7 (Drawing) Typical Intake Structure Section and Trashrack System

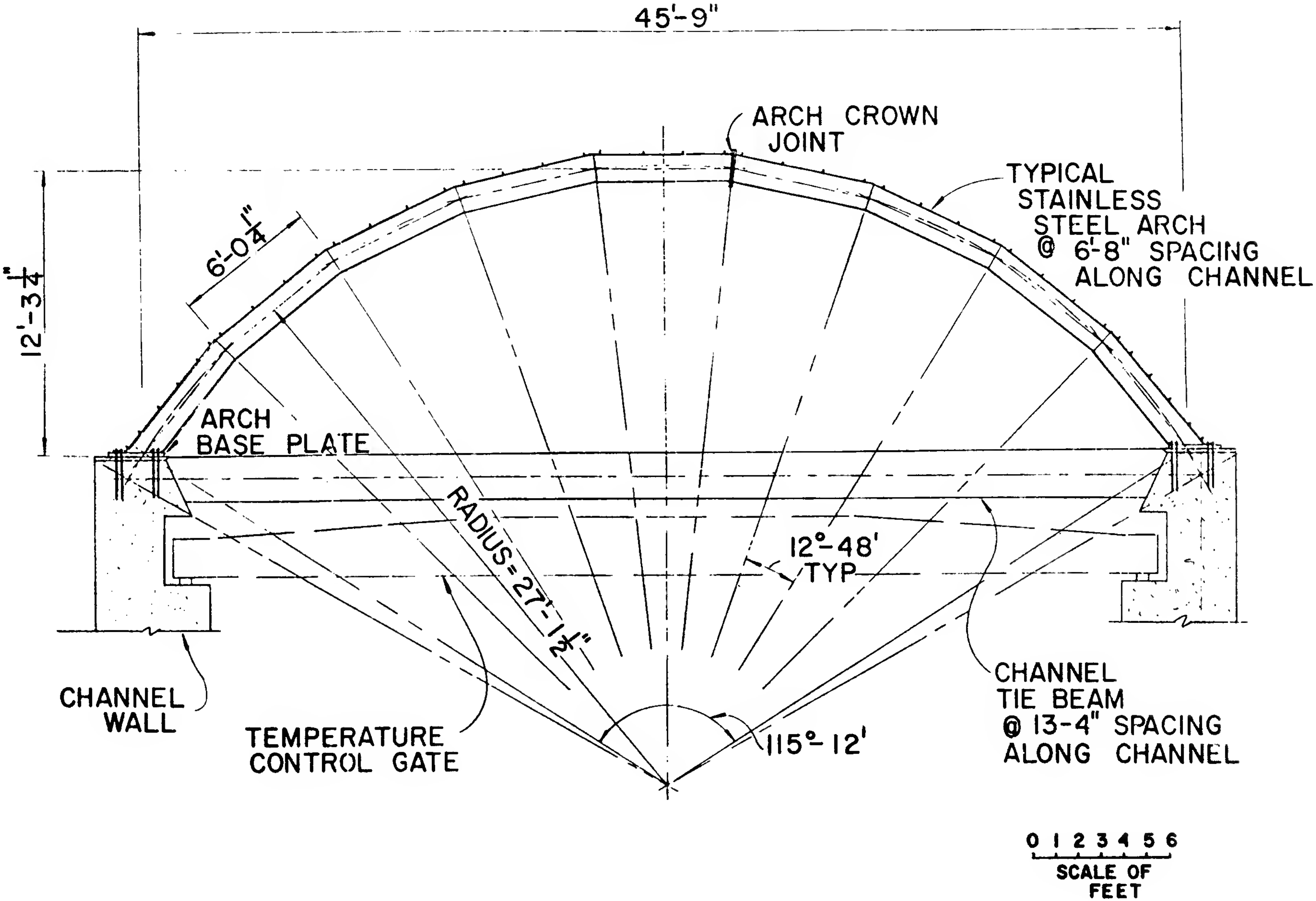


Exhibit 8 (Drawing) Typical Trashrack System Arch

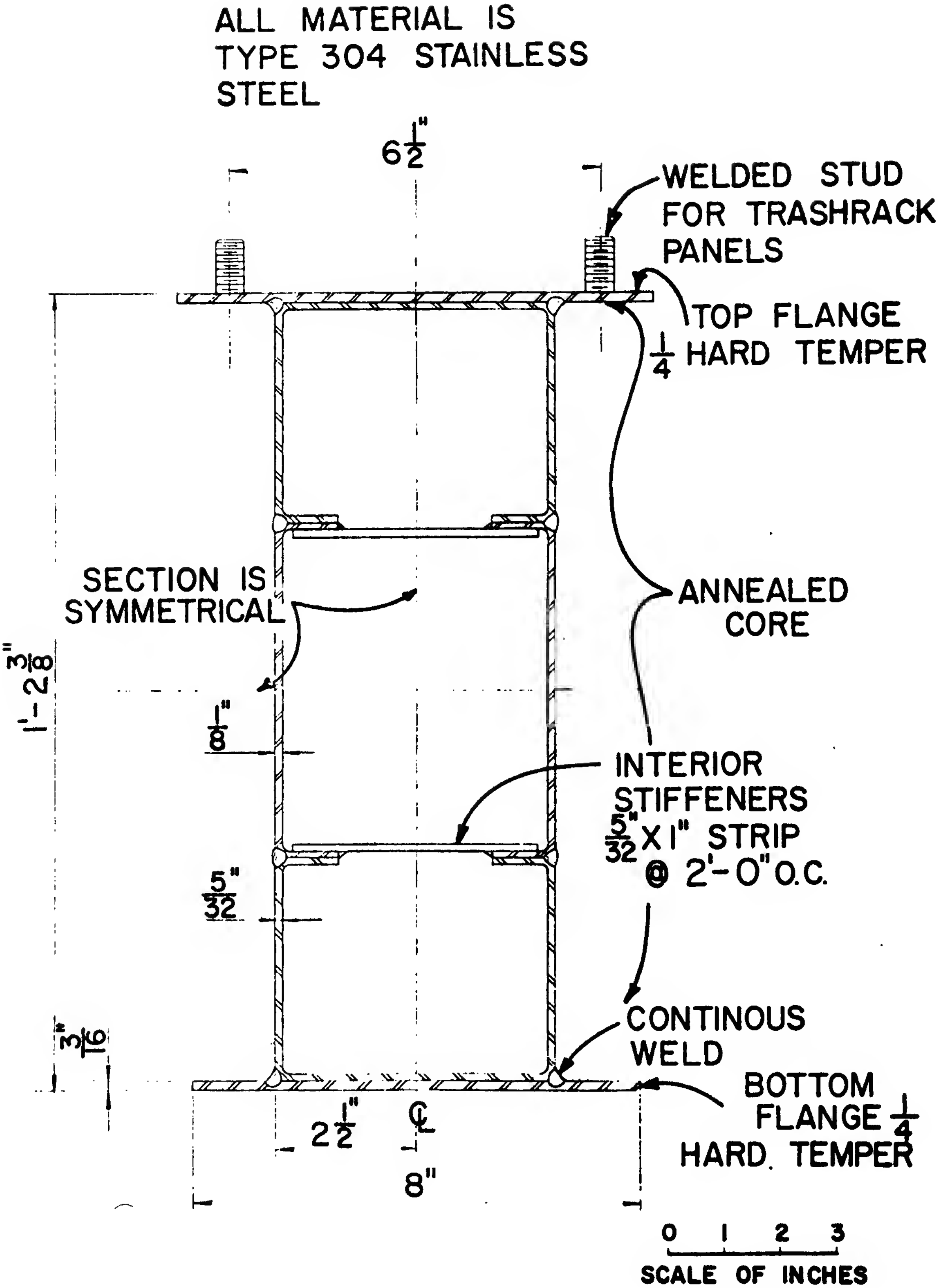


Exhibit 9 (Drawing) Typical Arch Cross Section

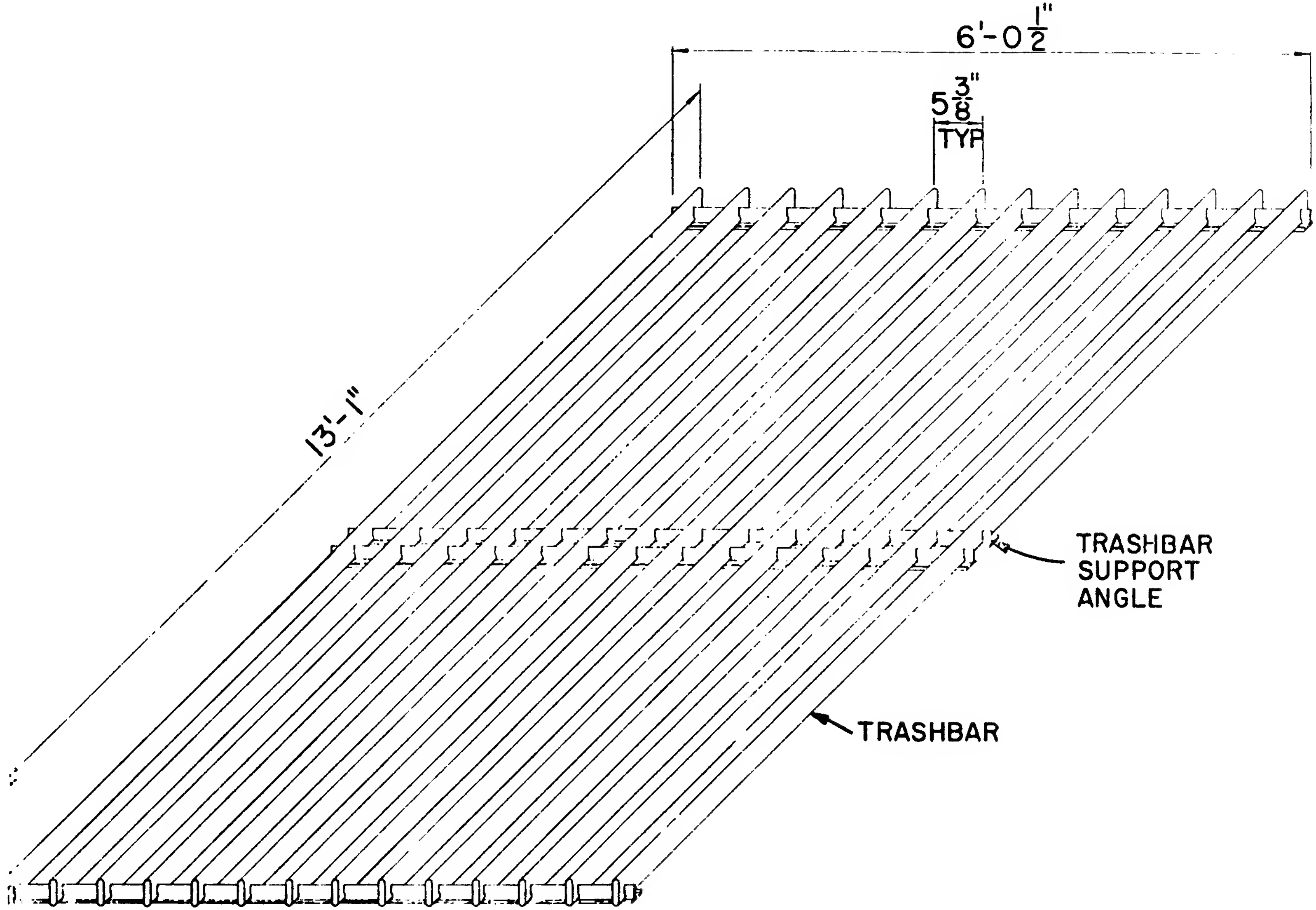


Exhibit 10 (Drawing) Typical Trashrack Panel

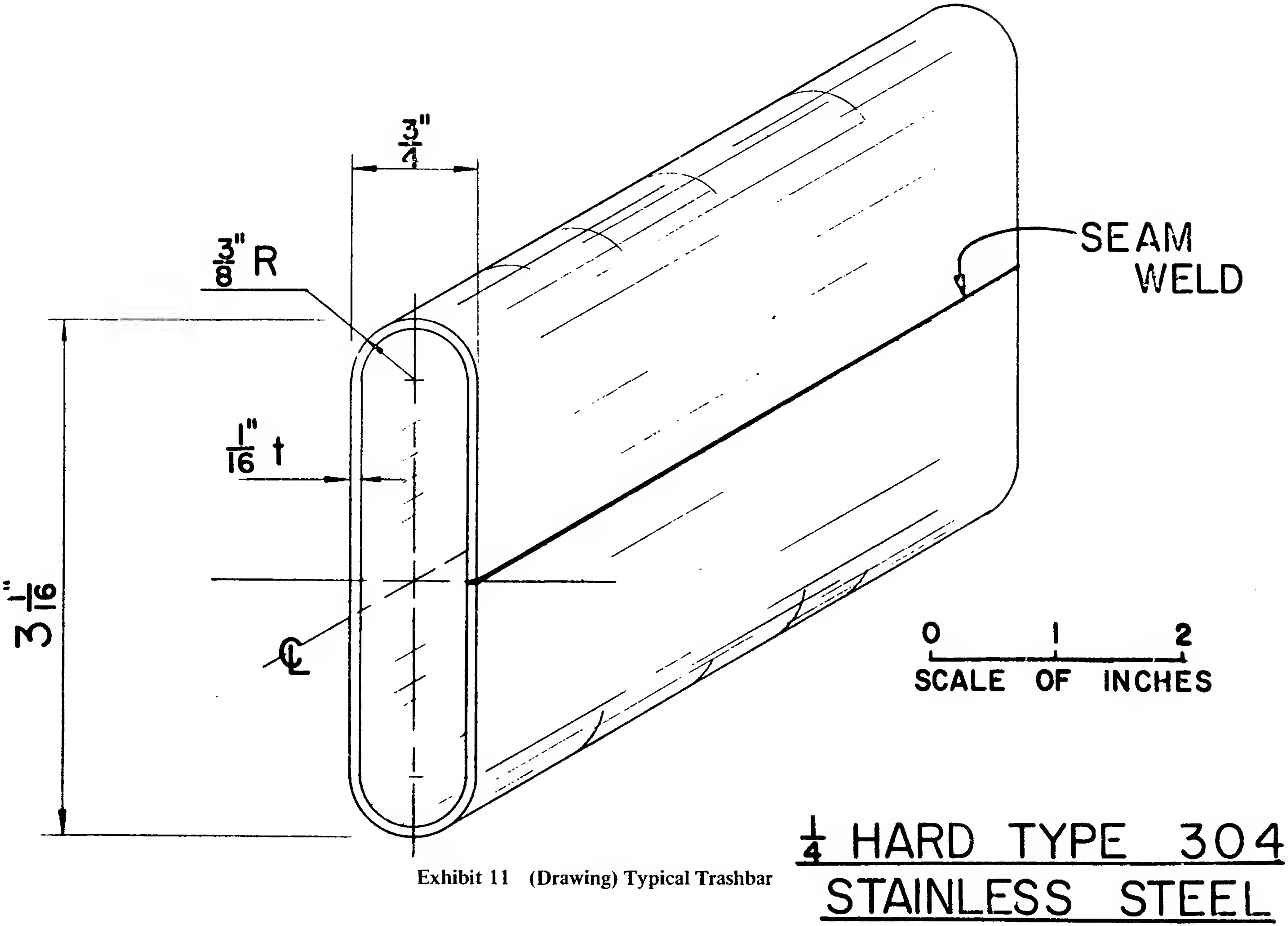


Exhibit 11 (Drawing) Typical Trashbar

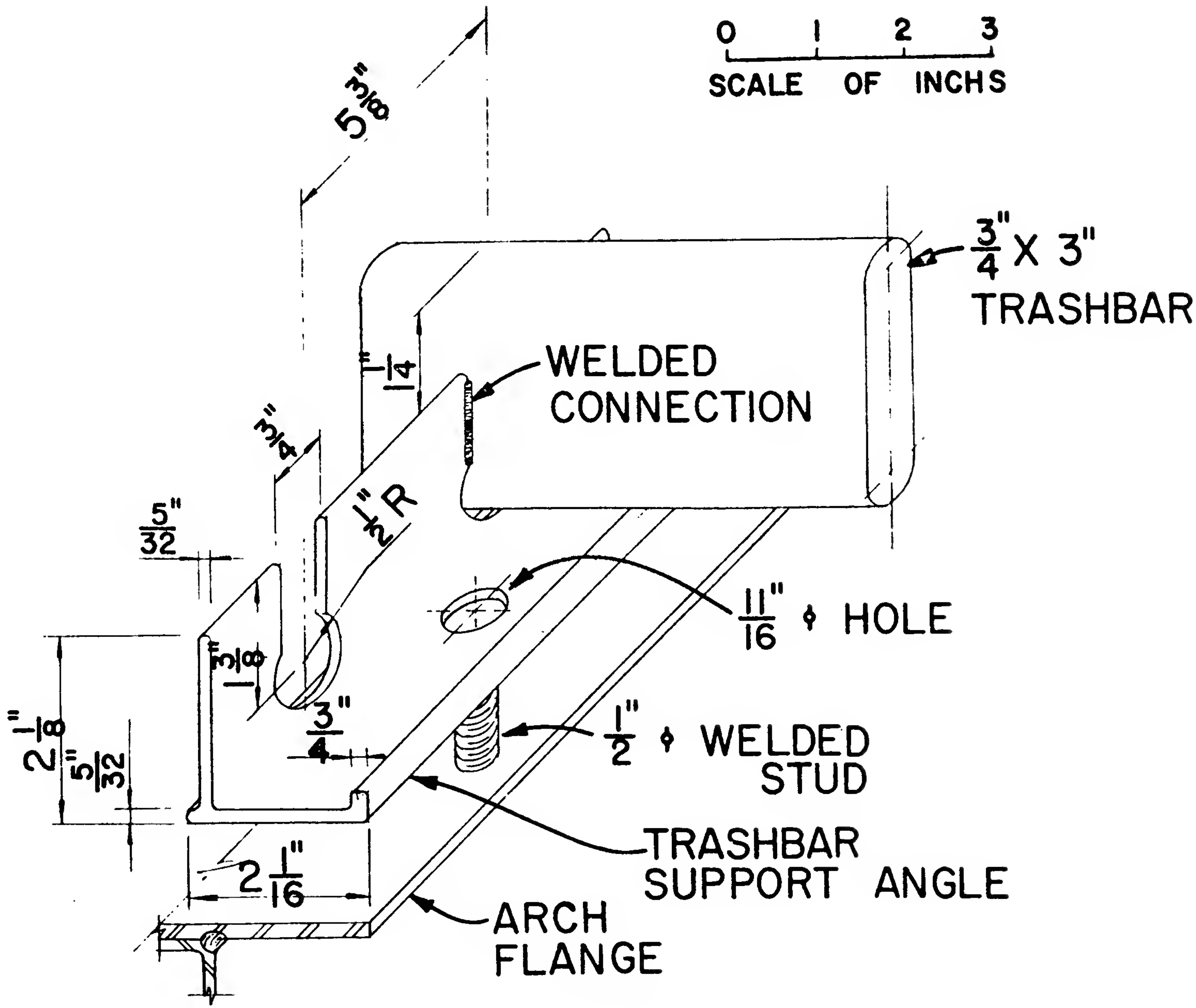
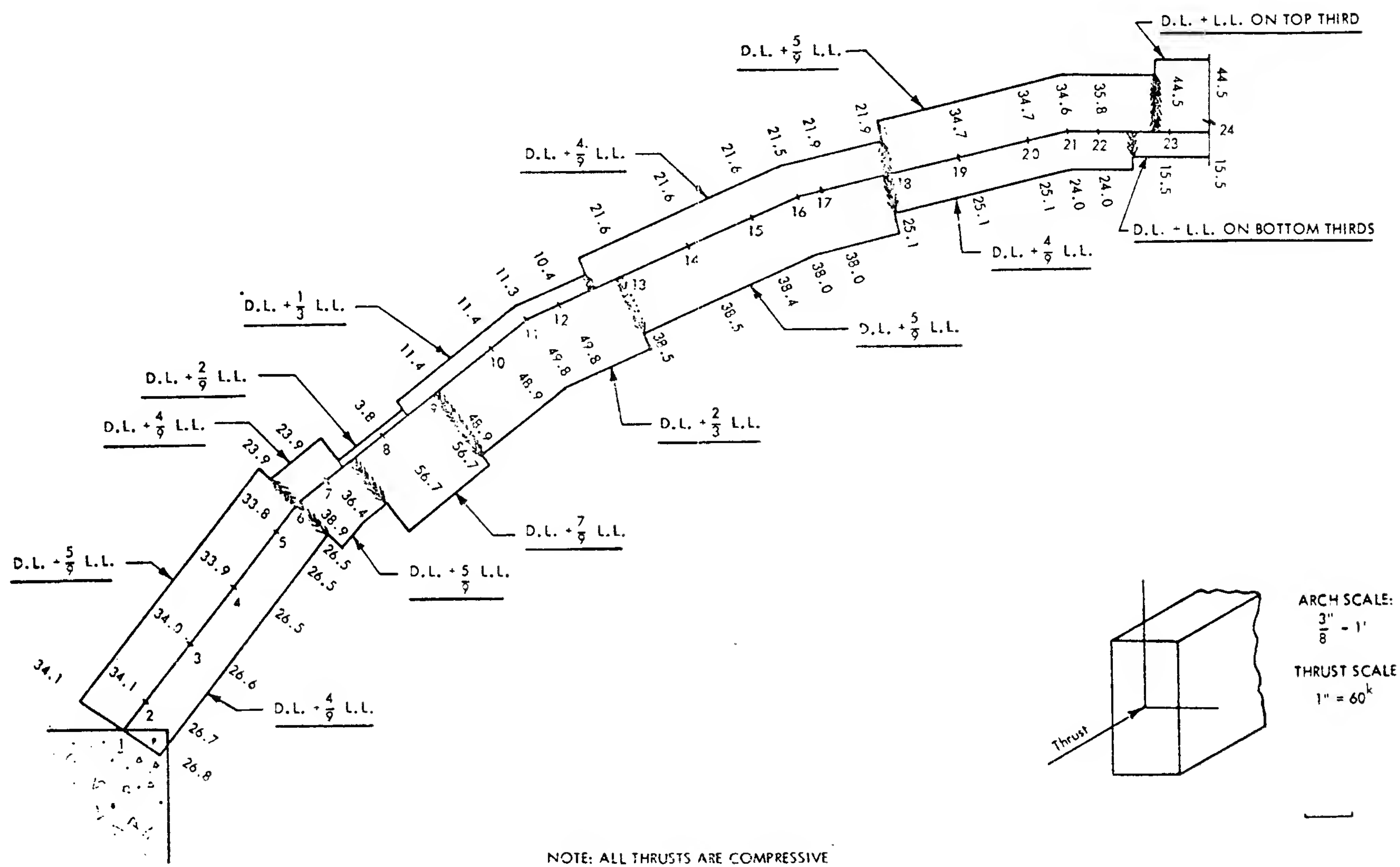


Exhibit 12 (Drawing) Trashbar Support Angle and Trashrack Connection



NOTE: ALL THRUSTS ARE COMPRESSIVE

Exhibit 13 (Drawing) Stainless-Steel Arch Thrusts Associated with Moment Envelope of Oroville Power Plant Intake Structure

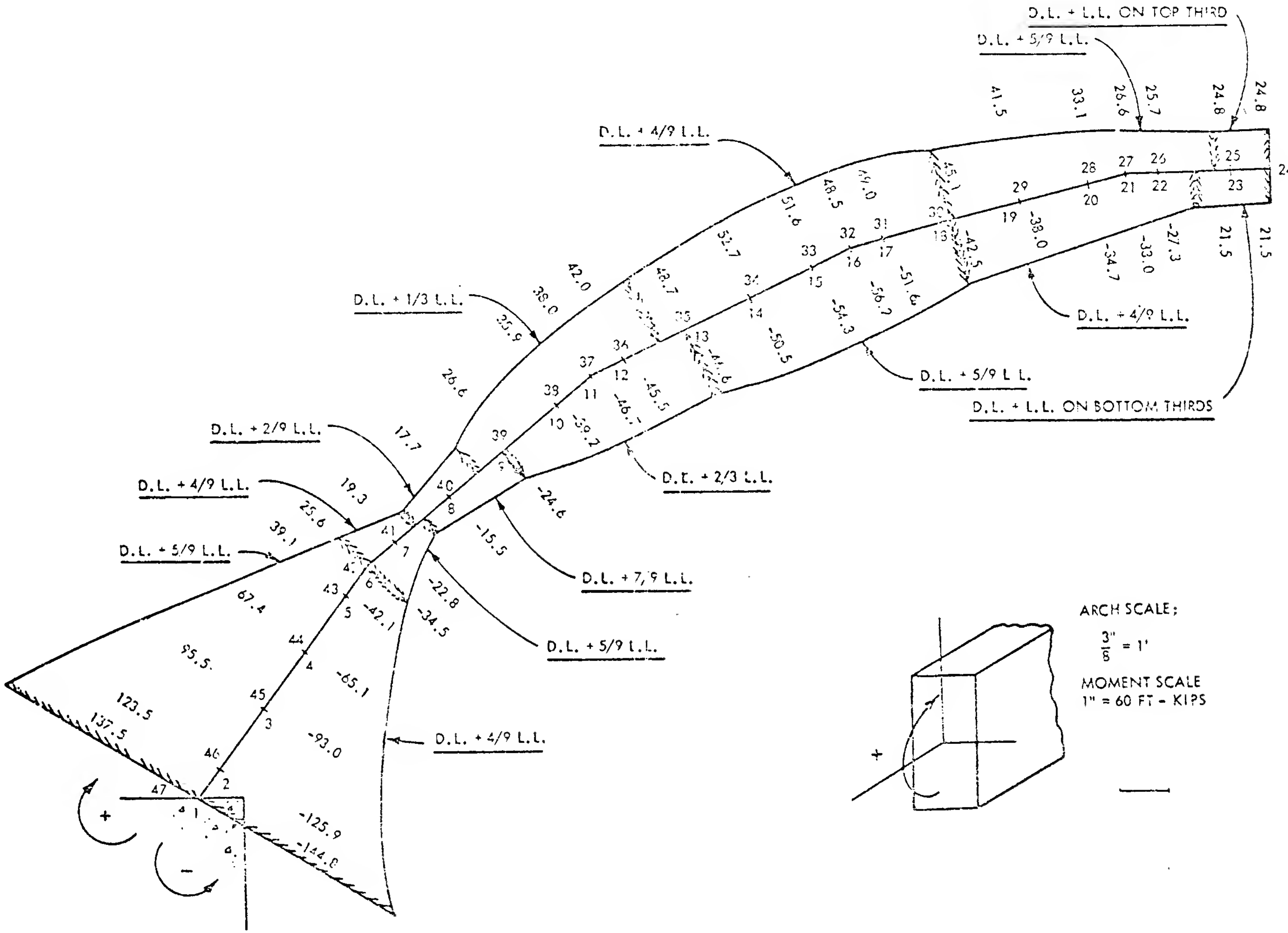


Exhibit 14 (Drawing) Final Design Moment Envelope for Stainless-Steel Arch of Oroville Power Plant Intake Structure.

Appendix I
Design Loads for the Trashrack System*

The loads for the trashrack system design had to be very carefully defined. The following is a discussion of these loads.

Dead loads or vertically acting gravity loads are quite important in this design. Because the plane of the arches is normal to the 1.9 to 1 slope of the intake, the vertically acting dead load resolves into a component that acts parallel to or in the plane of the arches and a component that acts normal to or out of the plane of the arches. This out-of-plane component is roughly equal to one-half the total structure dead weight. It can be seen that a trashrack system, light in weight, is advantageous. The total tonnage of the stainless steel system is approximately one-half the tonnage of the system in carbon steel. The advantage here in stainless is obvious.

Hydrostatic loads act normal to any surface. They are considered to be acting normal to the plane of the trashracks and, thus, in the plane of the arches. The design live load was set at 5 feet of water or about 312 pounds per square foot of projected area.

The hydrodynamic seismic loads can contribute to any component of arch loading. The most critical application of these loads was in an orientation that would add their magnitude to the out-of-plane component of dead load. A standard method was used to determine the virtual mass of water active with the structure during an earthquake; an acceleration equal to one-tenth gravity was used to evaluate the seismic forces.

Wind and wave loads, when combined with the structure dead loads, did not produce a load condition on the main structure that was as large as the condition of dead plus live loads. However, individual trashbars within the trashracks were checked for a load of 10 feet of water or 624 pounds per square foot of tributary area. These bars were also checked for impact by a one-ton log. These checks ensured the adequacy of the trashbars during high individual loadings.

Support movements and thermal changes cause stresses in a restrained structural system. These stresses could have become very troublesome in the trashrack system. Even though the reinforced concrete structure supporting the trashrack system is quite stiff, some small deflections and rotations of the arch support points could be anticipated. In addition, since austenitic stainless steels have a coefficient of thermal expansion approximately one and one-half times that of carbon steel, thermal change stresses, if not recognized and provided for, could have torn the structure apart. Over the long axis of the intake, expansion-contraction joints are provided in the trashrack system every forty feet. (These joints are discussed as a part of the trashrack connection details.)[15] Across the structure, the combined effects of support movements and thermal changes were taken into account by providing an arch that is fairly flexible. The arch can take the minor end displacements without causing internal stresses that are damaging to the structure.

*This discussion comprises the appendix of Reference 15.

Appendix II
Design of Arch to Support Trashrack Panels*

As already discussed, the function of the curved beam or arch in Exhibit 7 is to support the trashrack panels for the Oroville Dam Intake Structure. The fixed end arch consists of nine straight segments of 6 feet each which together approximate a segment of a circle whose radius is 27.14 feet. The design load in the plane of the arch is 5 feet of differential head over any or all portions of the area tributary to the arch, and the out-of-plane loads include the dead-weight component and seismic forces.

The effect of the above described in-plane and out-of-plane loads was analyzed via the Column Analogy[17] and the Shear and Torsion Analogy,[18] respectively. Computer programs for each of these computational techniques were developed by the Structural Design Section for the arch as shown in Exhibit 8.

The preliminary analysis, based on a constant E and on I, yielded a design moment envelope similar to that in Exhibit 13. Because the moment was the primary stress producer, the thrust envelope was plotted according to the associated design moment as shown in Exhibit 14. From these preliminary calculations it was found necessary to make the seven interior segments capable of carrying 60 foot-kips of moment with 35 kips of thrust and the two exterior segments capable of carrying 140 foot-kips of moment with 35 kips of thrust.

In the design of the interior segments, several alternative cross sections were investigated. Annealed and strain hardened cross sections were first considered. The scheme chosen, however, was a hybrid unit consisting of an annealed box with ¼-hard cover plates. It was found that with this combination, adequate rigidity could be achieved with minimum overall cost.

The geometry of the web element, a 14-by-5-inch box section, has two functions. The out-of-plane loads induce torsion and bending about the minor axis on the cross section. A closed section is torsionally stiff and the 14-inch web gave good minor axis area. (It should be mentioned, however, that the majority of the out-of-plane forces were removed from the arch via a secondary support system.) The other function of the box section is to provide two points of support for the flange element. The effect of having two supports as opposed to one is an increase in the critical buckling stress here of 20 ksi.

The four 1-1/8-inch protrusions into the interior of the arch (see Exhibit 9 which is Section A-A of Exhibit 8) also have a dual purpose. Not only do they make the cross section more convenient to fabricate, but they also stiffen the web elements as a whole, such that the full yield stress of 32 ksi may be developed before buckling will occur.

The end segments (adjacent to the base plates) provided the greatest problem insofar as design was concerned. The original thought was to make these segments hybrid units also; but the welded connection at the fixed base plate with the high moment capacity necessary at this point made this scheme impractical. The solution in this case was to replace the ¼-hard, 8-gage cover plates with 5/16-inch annealed cover plates flared from an 8-inch width where it joins the ¼-hard flange to 13 inches where it is welded to the base plate. The effect of this substitution is to ensure that in no case will the stress in the area of a weld be higher than that allowed for annealed stainless steel. This approach is conservative but

*This discussion comprises the appendix of Reference 16.

necessary, however, until further research into the effects of welding of strain-hardened stainless steel is done. The flaring also provided added stability at the base plates.

Having established the cross section throughout the length of the arch, the structure was reanalyzed to find the effect of the variable moment of inertia and variable modulus of elasticity as explained in the computational techniques. In this final analysis which is reflected in Exhibits 13 and 14 and as expected, a minor redistribution of moment took place with the moment increasing by approximately 10% at the base and decreasing by about 8% at the crown. The base segment which was designed according to working stress design theory has a final maximum stress level of 21 ksi. The interior segments have a final minimum safety factor as defined earlier of 2.3 which is slightly above that required by the plastic design approach.

More details on the final structure are given in Plates 5 and 6 of the appendix to Reference 16.

References

1. Stainless Steel Data Sources*

   Allegheny Ludlum Steel Corporation, San Francisco, Calif.
   Armco Steel Company, Lafayette, Calif.
   Carpenter Steel Company, San Francisco, Calif.
   H. M. Harper Company, Berkeley, Calif. (Bolts, nuts, extrusions).
   Republic Steel and Tube, San Francisco, Calif.
   U.S. Steel, San Francisco, Calif.
   Pacific Tube Corporation, Los Angeles, Calif.

2. Watter, Michael and Lincoln, Rush A., "Strength of Stainless Steel Members as a Function of Design," Allegheny Ludlum Steel Corporation, Pittsburgh, Pa., 1950.

3. Peery, David J. "Aircraft Structures," McGraw-Hill Book Company, 1950.

4. "Welding, Brazing, Soldering and Hot Cutting Republic Enduro Stainless Steels," Republic Steel Corporation, Cleveland, Ohio, 1952.

5. Bleich, Fredrich, "Buckling Strength of Metal Structures," McGraw-Hill Book Company, 1952.

6. Krivobok, V. N., Mayne, C. R., Paret, R. E., and McKelvey, A. J., "Forming of Austenitic Chromium-Nickel Stainless Steels, International Nickel Company, New York, N.Y., 1954.

7. "Stainless Steel Fabrication," Allegheny Ludlum Steel Corporation, Pittsburgh, Pa., 1959.

8. "Plastic Design in Steel," American Institute of Steel Construction, New York, N.Y., 1959.

9. "Design Manual for High Strength Steels," U.S. Steel Corporation, Pittsburgh, Pa., 1962.

10. "Light Gage Cold-Formed Steel Design Manual," American Iron and Steel Institute, New York, N.Y., 1962 (Include Commentary).

11. "Stainless and Heat Resisting Steels," American Iron and Steel Institute, New York, N.Y., 1963.

12. Lenamond, Norris G., and McDonald, Jose Jr., "Investigation of the Properties of Welded High Strength Stainless Steels," International Nickel Company, New York, N.Y., 1964.

13. Frost, Ronald W., Schilling, Charles G., "Behavior of Hybrid Beams Subjected to Static Loads," J. Structural Division, ASCE, 90, No. ST3, Proc. Paper 3928, June 1964.

14. Augusti, Giuliano, "Behavior of Hybrid Beams Subjected to Static Loads," J. Structural Division, ASCE, 90, ST6, Discussion of Proc. Paper 3928, December 1964.

15. Gilbert, Paul H., "Trashrack System Design for the Oroville Dam Powerplant Intake," presented to National Association of Corrosion Engineers, Western Regional Conference, Corrosion Engineering Symposium, Honolulu, Hawaii, November 9, 1965.

16. Gilbert, Paul H., and Griffith, Alvin R., "A Design Guide to Structural Stainless Steel," Technical Memorandum 15, Dept. of Water Resources, State of California, 1965. (Reprinted as Publication A-495, The International Nickel Co., Inc.).

17. Cross, Harry, "The Column Analogy" Bulletin No. 215, Engr. Experiment Station, University of Illinois, Urbana, Ill., 1930.

18. Baron, Frank and Michalos, James P., "Laterally Loaded Plane Structures and Structures Curved in Space," Trans. ASCE, 117, Proc. Paper 2493, 1952.

19. Gilbert, Paul H., "Corrosion-Resistant Construction," Power Engineering Magazine, January 1968, pp. 56-58. (Reprinted by The International Nickel Co., Inc.).